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14. ABSTRACT
The ultimate goal of this research is to enhance the understanding of global ocean noise and how variability in sound level impacts marine mammal acoustic communication and signal detection. How short term variability and long term changes of ocean basin acoustics impact signal detection will be considered by examining 1) the variability in low frequency ocean sound levels and sources, and 2) the relationship of sound variability on signal detection as it relates to marine mammal active acoustic space and acoustic communication. This work increases the spatial range and time scale of prior studies conducted at a local or regional scale. The comparison of acoustic time series from different ocean basins provides a synoptic perspective for observing and monitoring ocean noise on multiple times scales in both hemispheres as economic and climate conditions change. Quantified changes in the acoustic environment are then applied to the investigation of ocean noise issues related to general signal detection tasks, as well as marine mammal acoustic communication and impacts.

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Ocean Basin Impact of Ambient Noise on Marine Mammal Detectability, Distribution, and Acoustic Communication - YIP

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LONG-TERM GOALS

The ultimate goal of this research is to enhance the understanding of global ocean noise and how variability in sound level impacts marine mammal acoustic communication and signal detection. How short term variability and long term changes of ocean basin acoustics impact signal detection will be considered by examining 1) the variability in low frequency ocean sound levels and sources, and 2) the relationship of sound variability on signal detection as it relates to marine mammal active acoustic space and acoustic communication. This work increases the spatial range and time scale of prior studies conducted at a local or regional scale. The comparison of acoustic time series from different ocean basins provides a synoptic perspective for observing and monitoring ocean noise on multiple times scales in both hemispheres as economic and climate conditions change. Quantified changes in the acoustic environment can then be applied to the investigation of ocean noise issues related to general signal detection tasks, as well as marine mammal acoustic communication and impacts.

OBJECTIVES

The growing concern that ambient ocean sound levels are increasing and could impact signal detection of important acoustic signals being used by animals for communication and by humans for military and mitigation purposes is being addressed. The overall goal of the study is to gain a better understanding of how low frequency sound levels vary over space and time. This knowledge is then related to the range over which marine mammal vocalizations can be detected over different time scales and seasons. Over a decade of passive acoustic time series from the Indian, Atlantic, and Pacific Oceans are being used to address the following project objectives:

1. **Determine the major sources (or drivers) of variation in low frequency ambient sound levels on a regional and ocean basin scale.**
   A. What are the regional source contributions to low frequency ambient sound levels?
   B. Is there variation in source characteristics of the major low frequency source components over space and time?
   C. Is low frequency sound level uniformly increasing on a global scale?
2. **Investigate the impacts of variation in low frequency ambient sound levels on signal detection range, marine mammal communication, and distribution.**

A. How does species specific detection range (acoustic active space) vary on a daily, weekly, monthly, and yearly time scale?
B. Are low frequency vocalization detections related to changes in ambient sound level?
C. Do marine mammals exhibit any changes in calling behavior to compensate for noise?

APPROACH

The originally proposed effort was a comparative study of passive acoustic time series from the Comprehensive Nuclear Test Ban Treaty Organization International Monitoring System (CTBTO IMS) locations in the Indian (H08) and Equatorial Pacific (H11) Oceans over the past decade (Figure 1, Table 1). An additional site at Ascension Island (H10) in the Atlantic Ocean was added because it provides an additional southern hemisphere site for comparison. (Figure 1, Table 1). CTBTO monitoring stations consist of two sets of three omni-directional hydrophones (0.002-125 Hz) on opposite sides of an island. The hydrophones are located in the SOFAR channel at a depth of 600 to 1200 m, depending on location. The hydrophones are cabled to land 50-100 km away and connected to shore stations for data transmission. Individual datasets are calibrated to absolute sound pressure levels (SPL) in standard SI units, removing site-specific hydrophone responses. The sites are under the national control of the countries to which the hydrophones are cabled and data is available via AFTAC/US NDC (Air Force Tactical Applications Center/ US National Data Center) for US citizens.

Quantifying the relationship between factors affecting ocean sound variability and corresponding ecosystem response illustrates the effectiveness of passive acoustic monitoring and provides critical information needed for predictive modeling of signal detection probability. Project success is dependent on the appropriate time series analyses and comparisons over time at a single location and across locations. Whilc there is great scientific merit in quantifying the acoustic relationship between physical and biological parameters of the marine ecosystem, the integration of the acoustic datasets with ancillary data sets further enhances the value of the research by ensuring the appropriate comparisons are made between locations and over time at the same location. Remotely sensed chlorophyll concentration and sea surface temperature (SST) are being modeled for the targeted ocean regions to provide insight on the level of primary productivity within each area. Historical vessel data and movements were purchased through Lloyd's Marine Intelligence Unit (MIU). The database extends back to 1997, which is appropriate for obtaining shipping data over the same time periods and scales of the acoustic data and other ancillary datasets.

The unit of analysis, patterns, and trends of regional ocean sound level statistics stemming from last year's work have been combined with propagation modeling efforts to translate changes in sound level with changes in estimated signal detection area over different temporal scales. The OASIS Peregrine parabolic equation model was used to estimate regional transmission loss for incorporation into the sonar equation to determine signal detection range. Sound level statistics are a critical parameter set when describing noise and are fundamental to reducing the uncertainty of signal detection when applying the passive sonar equation. Signal detection range estimates then provided the spatial scale over which marine mammal vocalizations are being detected at each CTBTO IMS location.

WORK COMPLETED

This year's project focus was on 1) estimating the signal detection ranges and associated variability for each location, 2) producing a time series of SST, chlorophyll concentration, and primary productivity estimate time series for the regions around each IMS station, and 3) producing an hourly absence/presence detection time series for each vocalizing whale species. Data from three different CTBTO sites have been downloaded from the AFTAC/US NDC to ARL Penn State. The site locations and current data acquisition are shown in Table 2. Data continues to be downloaded on a monthly basis to keep the database current.

Signal Detection Area

Signal detection areas around CTBTO IMS monitoring stations at Diego Garcia (H08: Indian Ocean), Ascension Island (H10: Atlantic Ocean), and Wake Island (H11: Equatorial Pacific Ocean) were estimated using the passive sonar equation to determine the range along four bearings at which Signal Excess (SE) equaled zero (Equation 1). A constant source level (SL) of 180 dB re 1 μPa was used to be reflective of the range of estimated blue and fin whale vocalization source levels (Clark et al., 2009; Samaran et al., 2010; Širović et al., 2007). A detection threshold (DT) reflecting a 5% false alarm rate was determined from the actual sound level distribution at designated temporal scales, and directivity index (DI) and processing gain (PG) was assumed to be zero.

$$SE = SL - TL - NL - DT + DI + PG \tag{1}$$

Transmission loss (TL) for each season at each location was modeled 360° using the OASIS Peregrine parabolic equation (PE) model (in collaboration with Kevin Heaney, OASIS) for a receiver in the sound channel and a source within the upper 300 m of the water column to be consistent with the depth of vocalizing baleen whales (Figure 2). Peregrine is based on Michael Collins' split-step Padé PE marcher (Collins, 1993) (RAM), a widely used acoustic model for low to mid frequency undersea sound propagation modelling. Starting from Collins' RAMGEO 1.5 Fortran code, Peregrine has been ported to C, refactored for performance on modern computers, optimized for fully range-dependent problems, and is able to interpolate directly from geographically defined ocean field and bathymetry inputs. Seasonal sound speed profiles were obtained from The World Ocean Atlas. It includes an optional 3D azimuthal coupling operator, integrated time-domain output, range and depth antialiasing, volume attenuation, and two-parameter sediment specification (thickness and grain size) among other improvements. For broadband, Nx2D, and 3D problems, Peregrine will automatically use all available CPUs in parallel.

Noise level (NL) was calculated from acoustic recordings from a single north and south hydrophone at each CTBTO IMS monitoring location (see [Lawrence, 2004; Miksis-Olds et al., 2013] for details on CTBTO IMS monitoring stations and recording characteristics). NL measurements were made over three targeted 20 Hz bands (10-30 Hz, 40-60 Hz, 85-105 Hz) and are reported as spectral levels in decibels (dB re $1\mu Pa^2/Hz$). Mean spectral levels were calculated using a 15,000 point DFT Hann window and no overlap to produce sequential 1-min power spectrum estimates over the duration of the dataset.

Signal detection areas were estimated at three temporal scales: seasonal over 2011, monthly from 2010-2011, and daily over 30 days in November 2011. Detection range estimates were calculated from the maximum range along each bearing where SE >0. Straight lines were used to connect the range points along four bearings (0°, 90°, 180°, and 270°) to form a polygon, and the area within the polygon was calculated from the bearing range lengths. Signal detection ranges were not computed for the H10 North (N1) location at Ascension Island in the Atlantic Ocean due to a discrepancy between the hydrophone depth and local bathymetry. Effort is currently underway to resolve this with CTBTO personnel.

Satellite Products

The standard NASA satellite imagery MODIS-Aqua level 3 products were used to assess eight-day chlorophyll concentration ([Chl]), primary production and SST at 9km spatial resolution within each ocean basin (Figure 3). Primary production from the Vertical Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997) was obtained from the NASA MEaSUREs Ocean Color Product Evaluation Project website (http://wiki.icess.ucsb.edu/measures/Main_Page). SST and [Chl] were obtained from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov/). SST observations were acquired at night in the 4 μ nighttime microwave band. The NASA standard chlorophyll imagery product was utilized in each region (O'Reilly et al. 1998). All imagery time series were compiled from the start of the mission in June 2002 through the end of 2013. Pixels were extracted that were within the signal detection area for each frequency and season at each CTBTO IMS site. Any pixels within a water column less than 50 m deep were eliminated to ensure there were no bottom impacts in the satellite products.

Marine Mammal Detections

The hourly presence/absence of marine mammal vocalization detections was assessed in collaboration with Sharon Nieukirk (OSU) for the northern hydrophones at H11 Wake Island in the Equatorial Pacific and H08 Diego Garcia in the Indian Ocean. Multiple automatic detectors were assessed, but detector performance was inadequate. Consequently, manual detections were made hourly by species over the duration of the dataset. Currently efforts are now focusing on hourly detections on the southern hydrophones. Long term spectral averages were constructed over the duration of each data set at each northern location with a one hour window and 0.25 Hz resolution.

RESULTS

Signal Detection Area

Seasonal noise levels varied from 1-6 dB across frequency and location, which corresponded to a 1%-92% difference in signal detection area across seasons within a specific frequency at a particular location (Figures 4, 5). The signal detection area estimates in the Indian Ocean had the least amount of seasonal variability for 80 Hz and 100 Hz signals, but the seasonal variability in the detection area estimates for the lower frequencies examined (20 Hz, 30 Hz, and 50 Hz) varied over an order of magnitude at the northern hydrophone (Figure 5A). Detection areas were greater in the summer and fall compared to the winter and spring. The greatest amount of seasonal variation across ocean locations was observed in the Equatorial Pacific at Wake Island (H11) and ranged from 67%-96% (Figure 5C).

Monthly NL dB differences across locations over the two year period of 2010-2011 showed the general trend of higher variability at the northern sensors compared to the southern sensors (Figure 6). The monthly dB differences across locations mirrored the seasonal observations. The least variability in siganl detection area estimates were observed for 80 Hz and 100 Hz signals in the Indian Ocean at Diego Garcia (H08), and the most monthly variabiity was consistently observed across all frequencies at Wake Island in the Pacific (H11) (Figure 7).

The greatest amount of temporal variability in signal detection range was observed at the daily level and ranged from 25%-99% in November 2011. The distribution of signal detection range as a function of freqeuncy varied across locations (Figure 8). In the Indian and Atlantic Ocean locations, there was a large spread corresponding to order of magnitude differences observed at all frequencies (Figure 8A, 8B). In the Pacific Ocean at Wake Island, there was less vairation in the signal detection area estiamtes at 20 Hz and 50 Hz compared to the other 2 ocean locations (Figure 8C). The distributions for the 20 Hz and 50 Hz signal detection areas did not overlap with the 100 Hz distribution, indicating that signal frequency is an important parameter of detectability to consider in this region.

Satellite Imagery

The chlorophyll, primary productivity, and SST time series were highly correlated at each location with clear annual cycles (Figure 9). In the Indian Ocean, there was a decrease in both the magnitude and strength of the cyclic pattern for chlorophyll and primary productivity north of Diego Garcia from approximately 2006-2010. This feature was not as strong south of Diego Garcia (Figure 9A). The productivity was highest in the Indian Ocean near Diego Garcia compared to the other two CTBTO IMS locations. The magnitude of the peak chlorophyll and primary productivity oscillated between high and low years in the Atlantic Ocean near Ascension Island, while the magnitude of the SST remained uniform (Figure 9B). The magnitude and strength of the annual chlorophyll and primary productivity cycle was weakest in the Equatorial Pacific Ocean near Wake Island compared to the other two locations, yet the SST was comparable. If and how these patterns influence the presence of marine mammals detected through passive acoustic monitoring is currently being explored through statistical modeling.

Marine Mammal Detections

Long term spectral averages highlight the decrease in frequency of vocalization for blue whales in the Indian Ocean (Figure 10). There was not an analogous decrease in fin whale vocalizations observed at the Pacific Ocean location (Figure 10). Species detected at the Indian Ocean location include Antarctic, Madagascar, and Sri Lankan blue whales, fin whales, minke whales, U1, and U2 type calls. The U1 and U2 calls are attributed to blue whales of unspecified species (Sousa & Harris, in prep) (Figure 11). Species detected in the Pacific Ocean at Wake Island were fin, blue, minke and Bryde's whales(Figure 12). The factors that best predict whale presence at each location is currently being identified through statistical modeling. Factors be to include in the model are SST, chlorophyll, primary productivity, multiple sound levels, and shipping movements.

IMPACT/APPLICATIONS

The signal detection area work illustrates the order of magnitude differences in detection area as a result of changes in the soundscape over time. This study did not address difference in detection area as a result of transient sources such as passing vessels, rather the difference in detection area observed here reflect changes in the ambient conditions over daily, monthly, and seasonal scales. The percent difference in detection area estimates was a function of frequency and location. The greatest seasonal impact was observed at location H11 at Wake Island in the Pacific Ocean and highlights the need to take changing soundscape characteristics into account during passive acoustic monitoring or signal detection tasks. Distributions of daily signal detection areas as a function of frequency were not the same across ocean locations and demonstrate the need to understand the acoustic dynamics of an areas for obtaining the most accurate detection areas related to denisty estimation and signal detection. In order to translate the physical estimates of detection area into communication space and masking impacts for vocalizing marine animals, the hearing capabilities related to frequency bands, thresholds, and integration time would need to be combined with the physical attributes examine here (Clark et al., 2009). Based on the results of this exercise, it is clear that both humans and animals must constantly adjust their perceived range of signal detection to accurately interpret source location.

Generation of the long term spectral averages across the multi-year datasets revealed a dramatic decrease in freqeuncy of blue whale vocalizations. This is significant because it indicates that the use of automatic detectors for streamlining passive acoustic data processing need to be updated with the new signal characteristics over time. A detector developed for identifying Indian Ocean blue whale calls in 2002 would likely not be as effective in 2010.

TRANSITIONS

This project represents a transition from the acoustic characterization of local and regional areas to the characterization of ocean basins. Detailed knowledge of noise statistics and variation will contribute to reducing error associated with marine animal density estimates generated from passive acoustic datasets, signal detection and localization, and propagation models.

RELATED PROJECTS

The propagation modeling included in this study in collaboration with Kevin Heaney (OASIS) is directly related to ONR Ocean Acoustics Award N00014-14-C-0172 to Kevin Heaney titled "Deep Water Acoustics".

The current project is also directly related to and collaborative with ONR Ocean Acoustics Award N00014-11-1-0039 to David Bradley titled "Ambient Noise Analysis from Selected CTBTO Hydroacoustic Sites". Patterns and trends of ocean sound observed in this study will also be directly applicable to the International Quiet Ocean Experiment being developed by the Scientific Committee on Oceanic Research (SCOR) and the Sloan Foundation (www.iqoe-2011.org).

Sound level analysis of data from the Wake Island location is also to be used in a collaborative study of deep water sound propagation with Michael Ainslie, TNO. Collaborative efforts were joined to better understand the contribution and variation in distant shipping noise to local soundscapes (Ainslie & Miksis-Olds, 2013).

Results and efforts related to this award will directly benefit the follow-on work under ONR Award N000141410397 titled "Large scale density estimation of blue and fin whales."

The new project is collaborative with Len Thomas and Danielle Harris of CREEM, University of St. Andrews.

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PRESENTATIONS

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HONORS/AWARDS/PRIZES

Office of Naval Research Young Investigator Program (YIP) Award – 2011

Table 1. Acoustic sensor location summary. Latitude areas in parentheses under Latitude Region indicate acoustic focus of sensors on opposite sides of island.

Site	Element	Acoustic Focus	System	Location	Latitude Region of Sensor	Major Oceanogrphic Process
HA08	N	Equatorial Indian	CTBTO	Diego Garcia, UK	Low	Equatorial Current
	S	Indian	CTBTO	Diego Garcia, UK	Low (Mid)	Equatorial Current
HA11	N	W Pacific	CTBTO	Wake Is., USA	Low (Mid)	N Equatorial Current
	S	Equatorial Pacific	CTBTO	Wake Is., USA	Low	N Equatorial Current
HA10	N	Equatorial Atlantic	CTBTO	Ascension Is., UK	Low	S Equatorial Current
	S	S Atlantic	CTBTO	Ascension Is., UK	Low (Mid)	S Equatorial Current

Table 2. Data successfully downloaded and available to ARL Penn State.

Site/Location	Start Day	Most Recent Download	# Missing Days	Total Days	Total Years
HA08/Diego Garcia	01/21/2002	08/20/2014	40	4555	12.5
HA10/Ascension Island	11/04/2004	08/20/2014	4	3573	9.8
HA11/Wake Island	04/25/2007	08/20/2014	14	2660	7.2

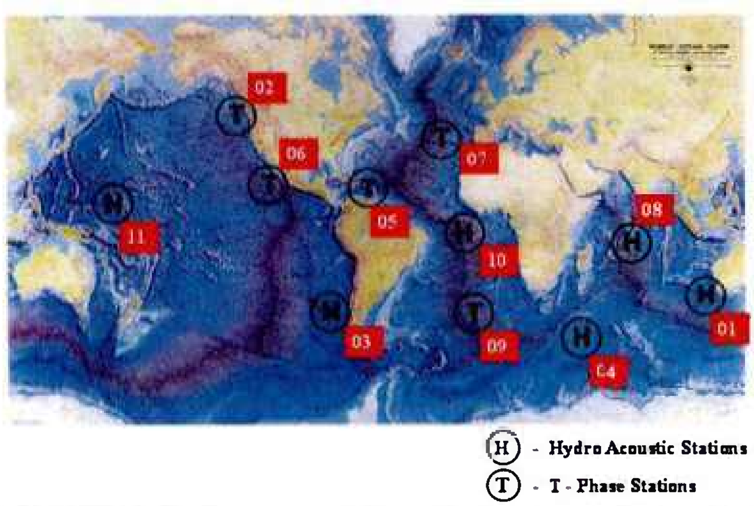


Figure 1. Location of CTBTO Hydroacoustic Sites. H sites denote hydrophone sites, moored in the water column at sound channel depths. T sites denote seismic "T-phase" sensors. This project will use data from H08, H10, and H11.

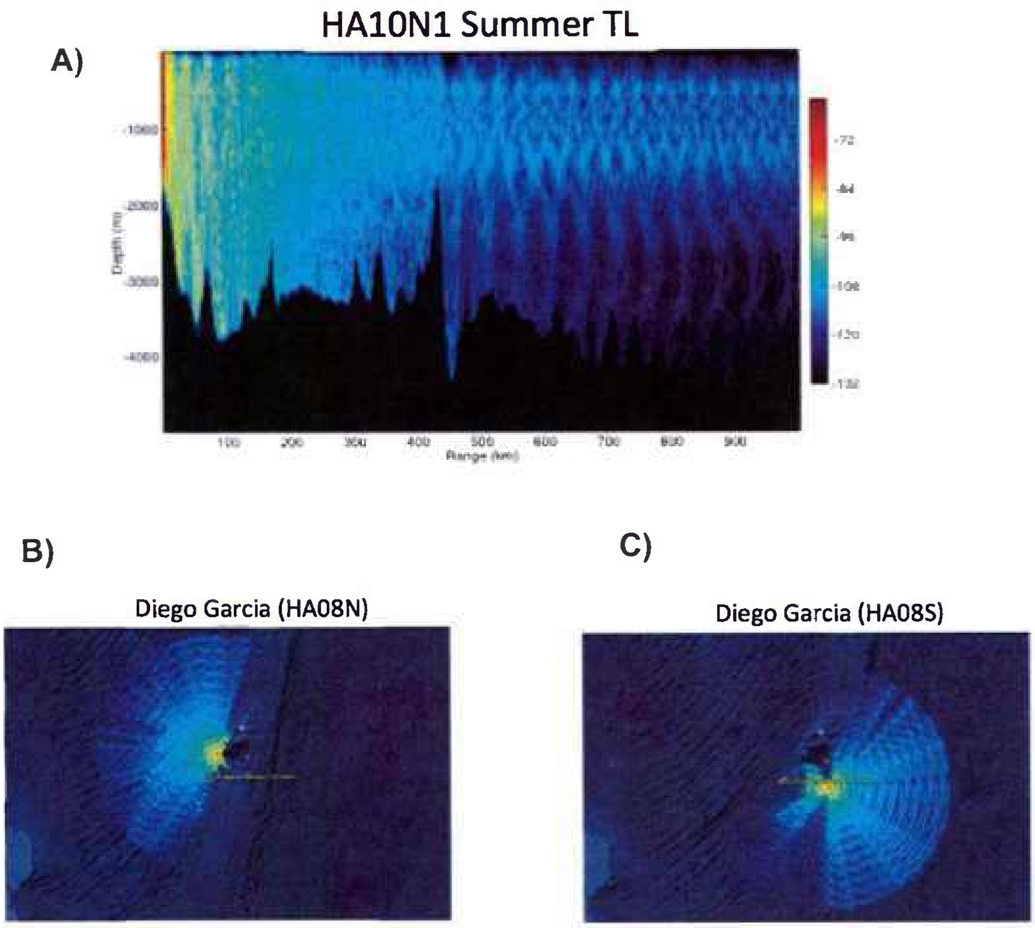


Figure 2. A) Receiver modeling TL output from the Peregrine PE model at CTBTO location at H10 N1 in the Atlantic Ocean at Ascension Island during the summer season. TL is shown as a function of depth and range. TL receiver output from the Peregrine PE model as a function of range around HA08 N1 (B) and HA08 S2 (C) in the Indian Ocean at Diego Garcia.

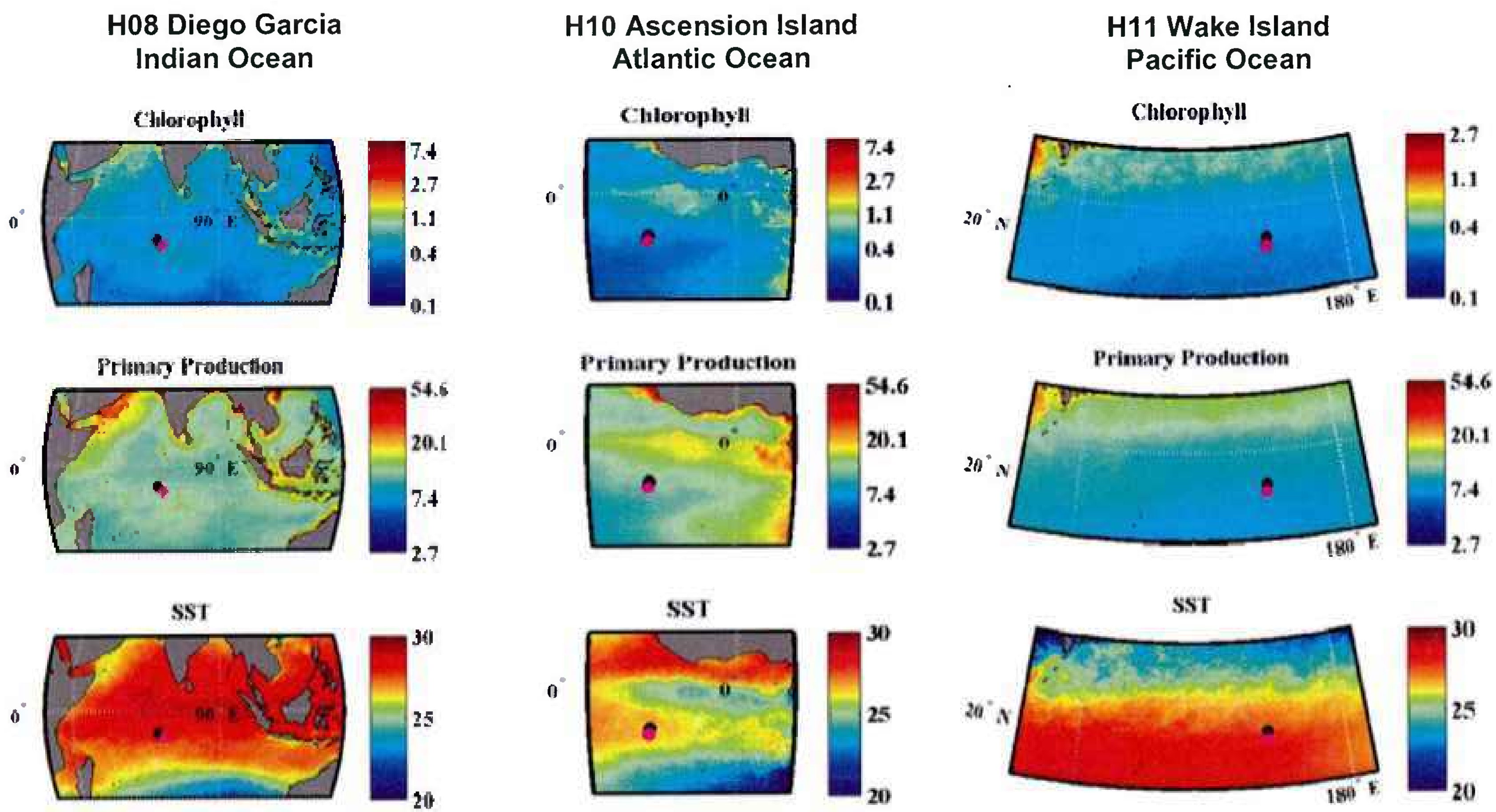


Figure 3. Yearly composite images from 2011 for chlorophyll (mg/m^3), primary production (mg C /m^{-2}/day) and Sea Surface Temperature (SST, degrees Celsius). The black marker indicates the location of the northern triad at each location, and the magenta marker indicates the location of the southern hydrophone triad.

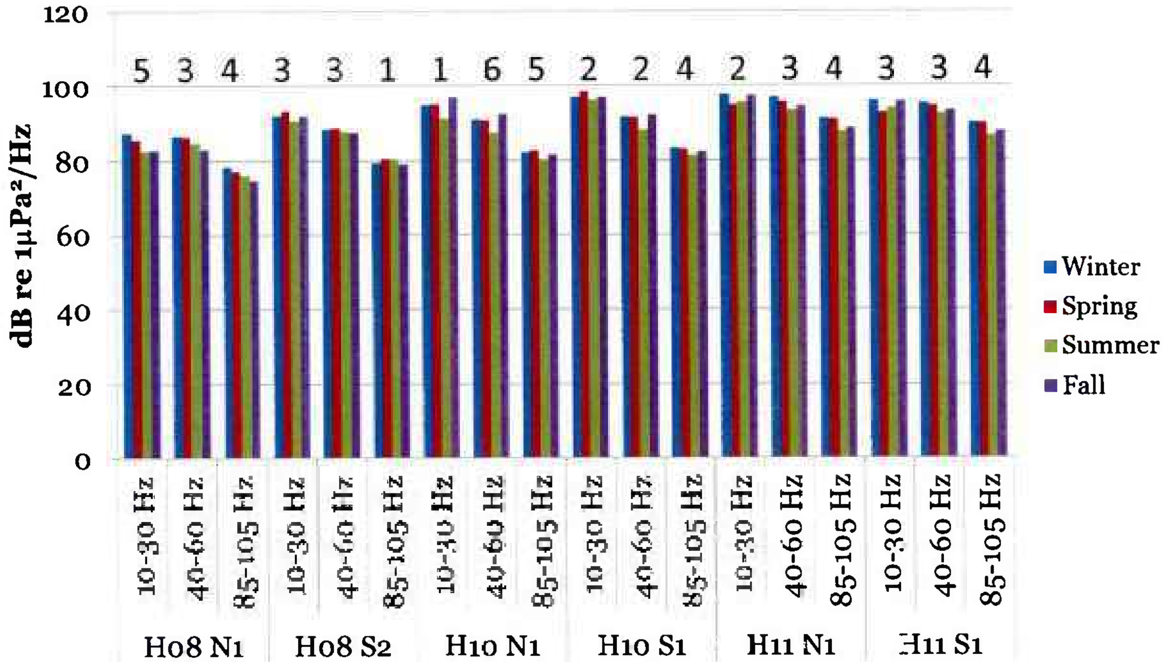


Figure 4. Mean seasonal spectrum levels in designated frequency bands. Numbers above each frequency band indicate the dB difference across seasons for that frequency band and location.

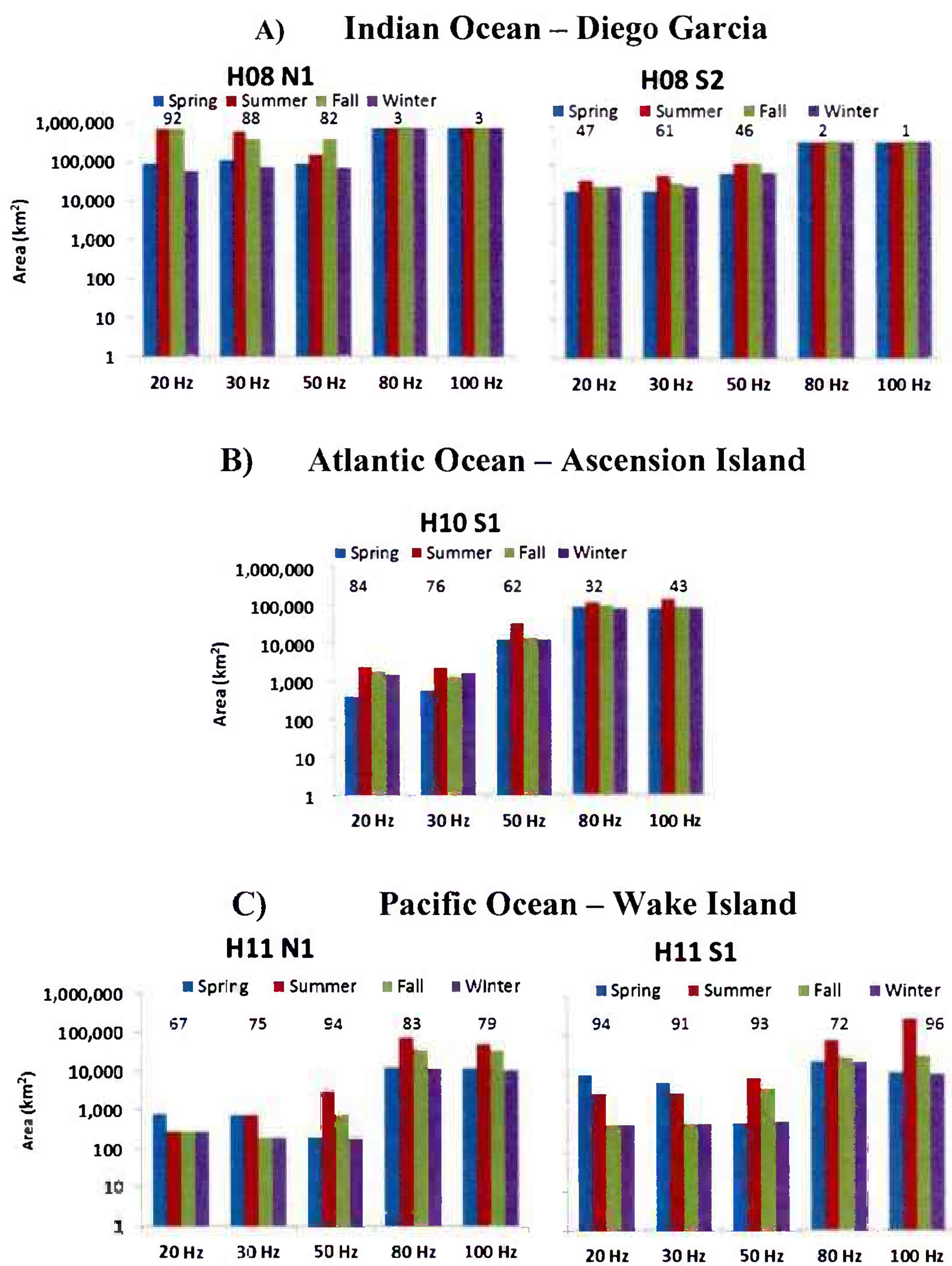


Figure 5. Estimates of seasonal signal detection area for the 5 modeled frequencies. Numbers above each frequency band indicate the % difference across seasons for that frequency band and location.

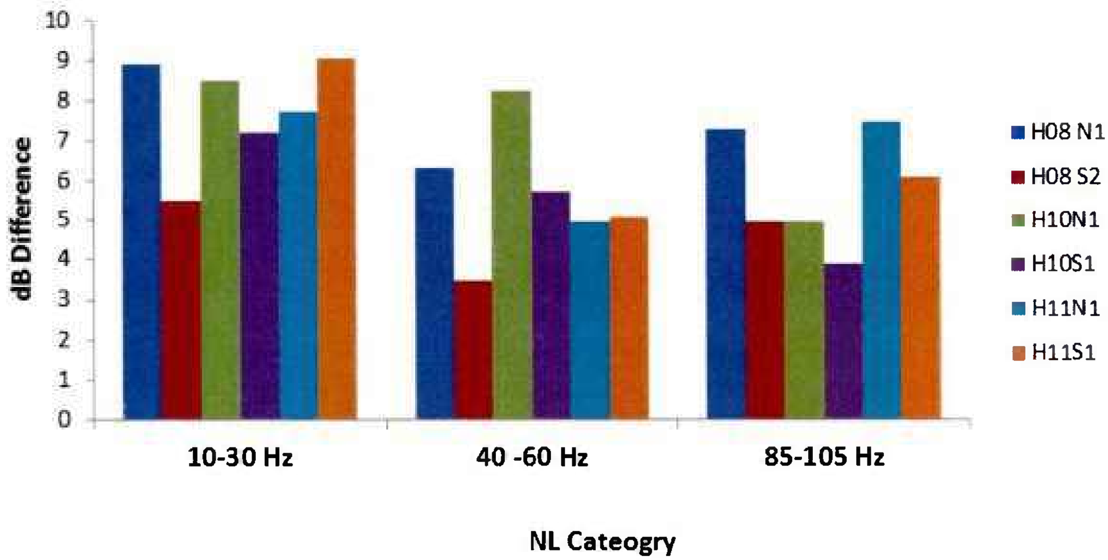


Figure 6. Monthly sound level dB difference over 24 months in 2010-2011 at each CTBTO IMS location.

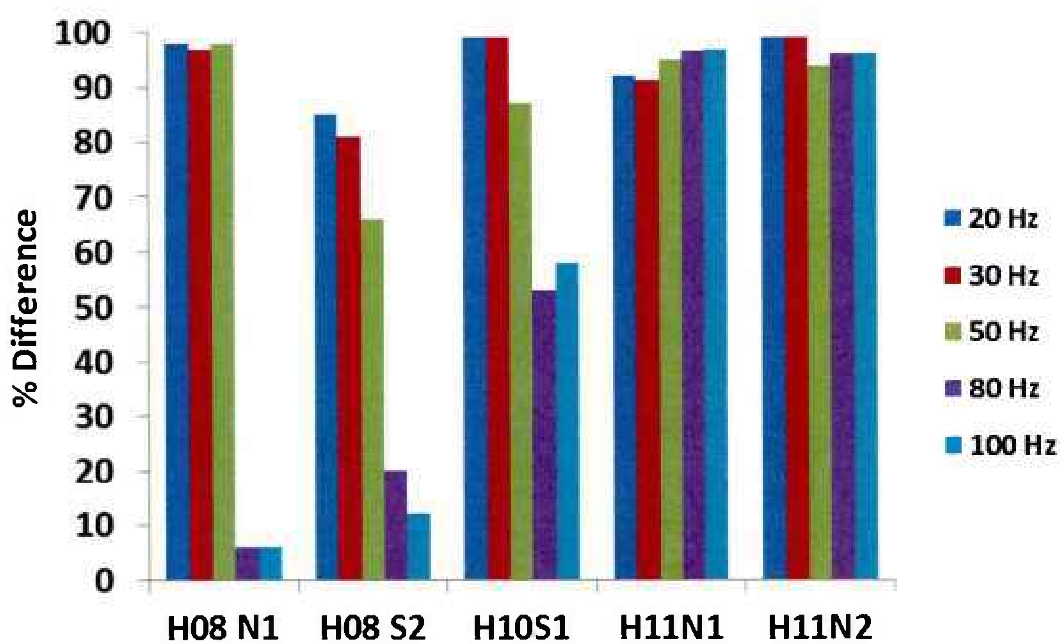


Figure 7. Monthly % differences in signal detection area estimates at each CTBTO IMS location as a function of signal frequency.

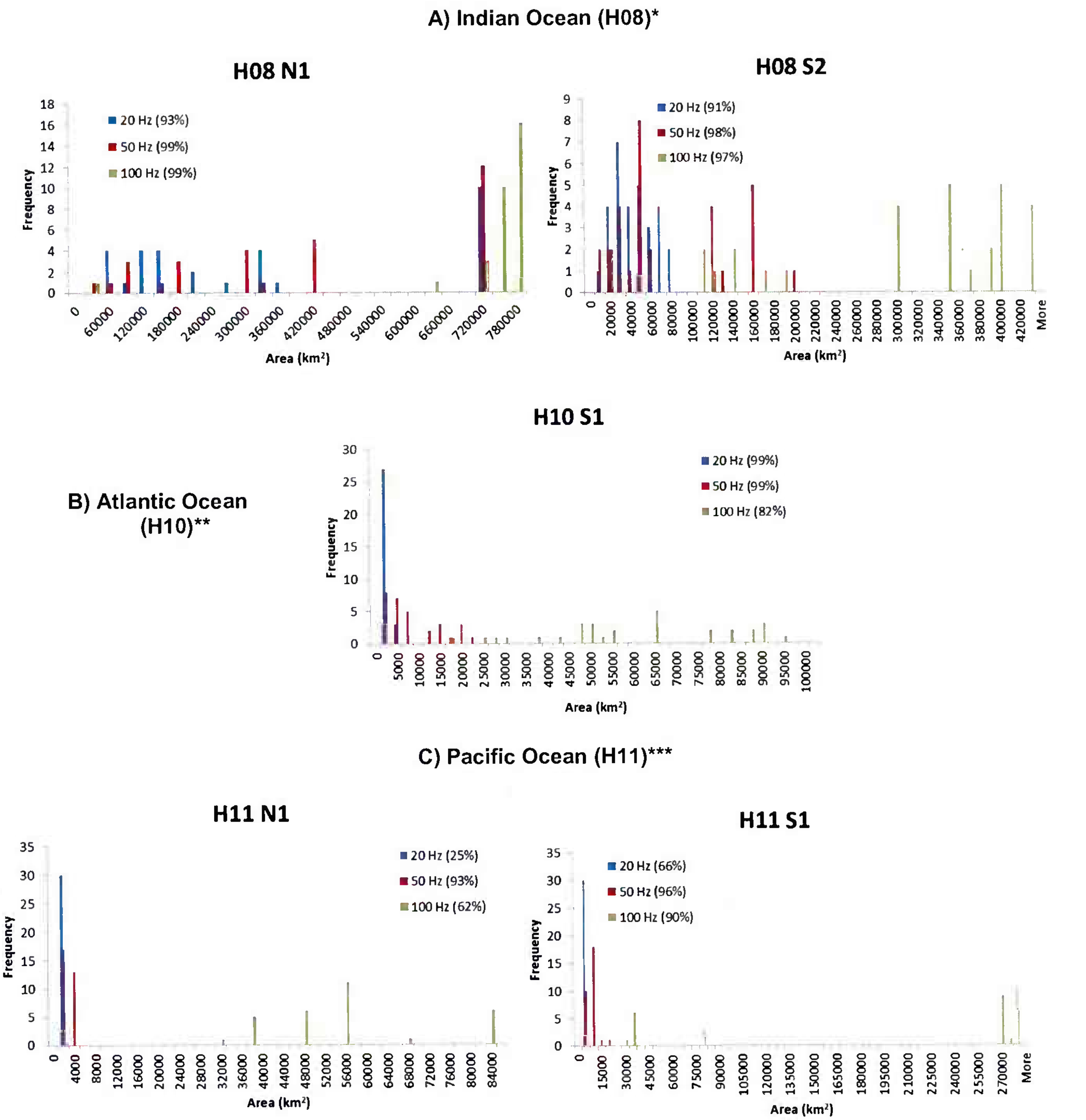
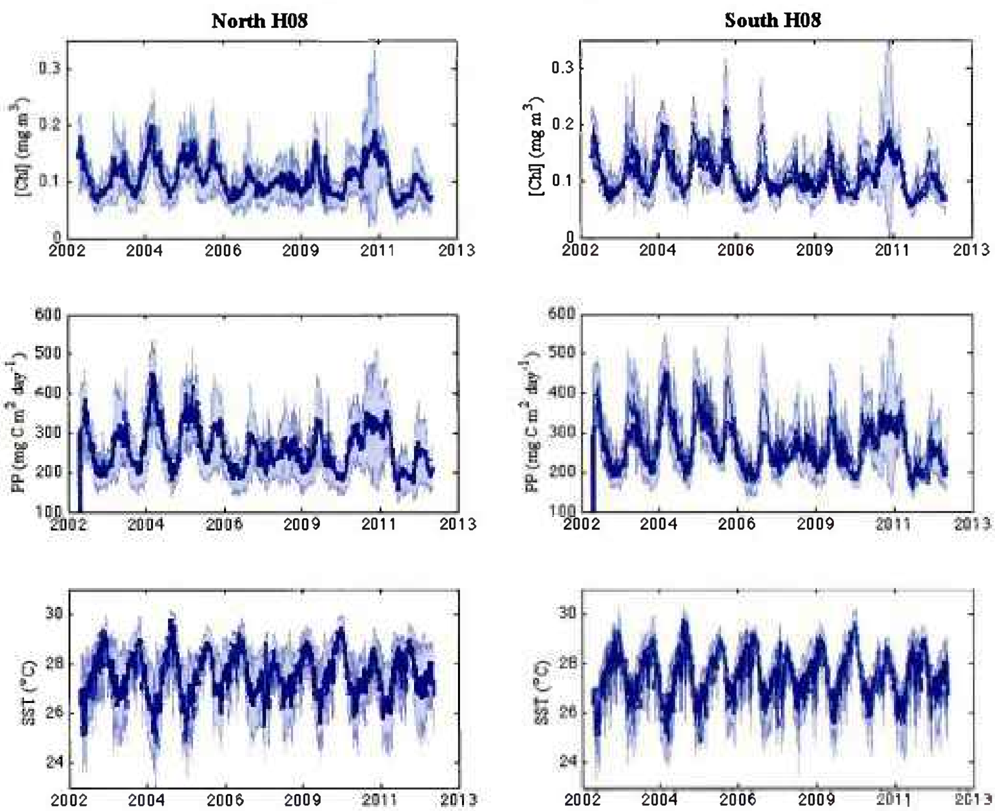
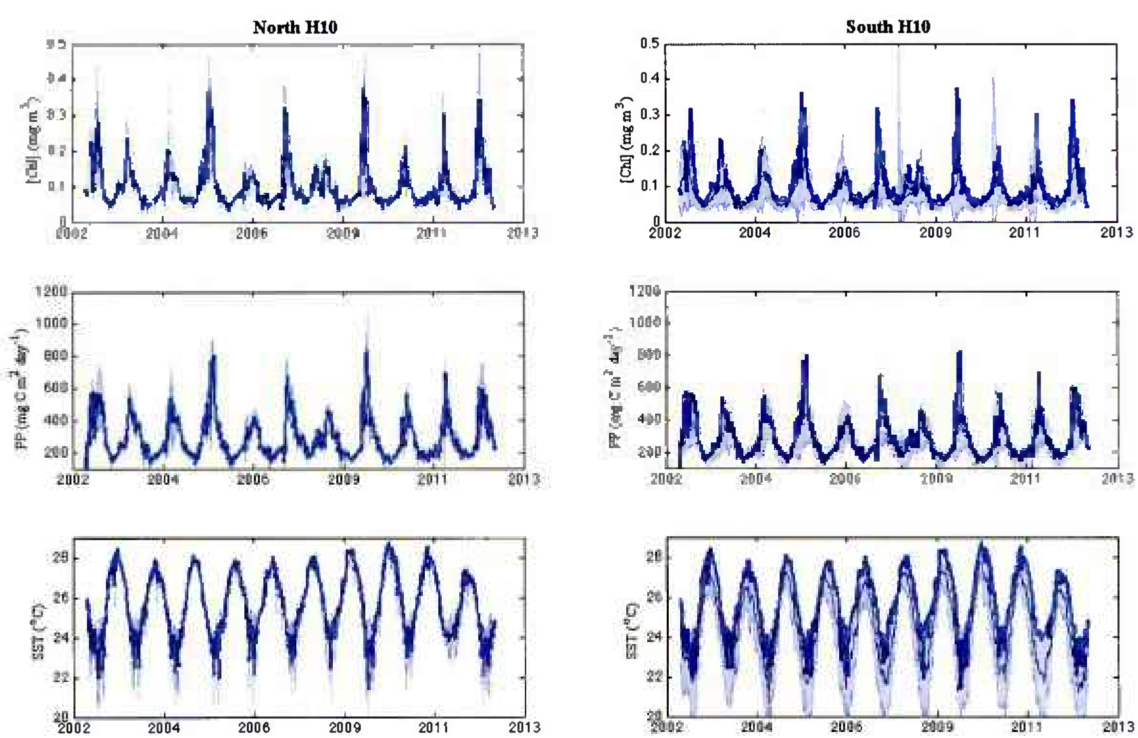


*Figure 8. Frequency distribution of daily signal detection area estimates in November 2011. The % values in the legend represent the signal detection area % difference over the course of the month. * denotes the trend over a 10 year dataset. ** denotes the trend over an 8 year dataset. *** denotes the trend over an approximate 6 year dataset.*

A) **Indian Ocean – Wake Island**



B) **Atlantic Ocean – Ascension Island**



C) **Pacific Ocean – Wake Island**

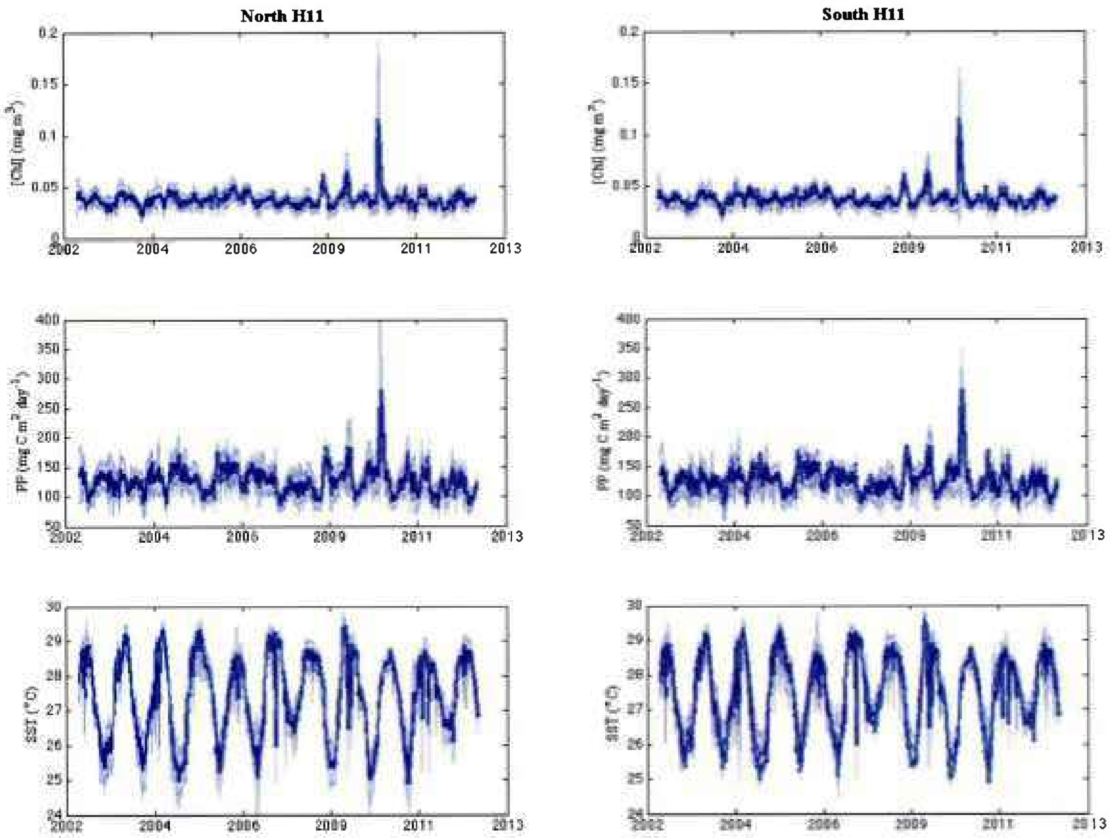


Figure 9. Times series of chlorophyll, primary productivity, and SST estimated from satellite imagery in the A) Indian Ocean, B) Atlantic Ocean, and C) Pacific Ocean. The bold blue line represents the average over 5 signal detection areas corresponding to the 5 signal frequencies, and the light gray area is the standard deviation.

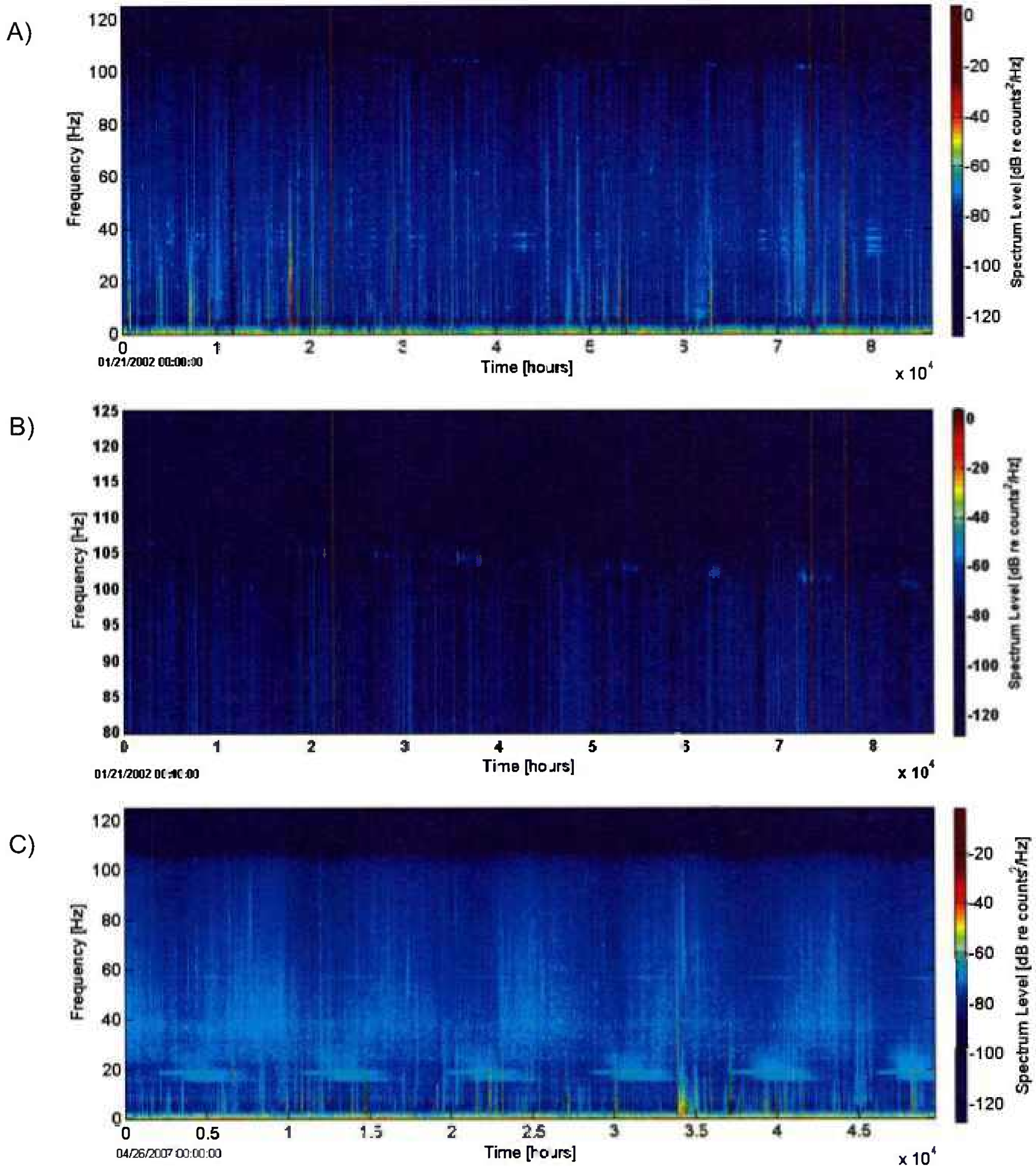
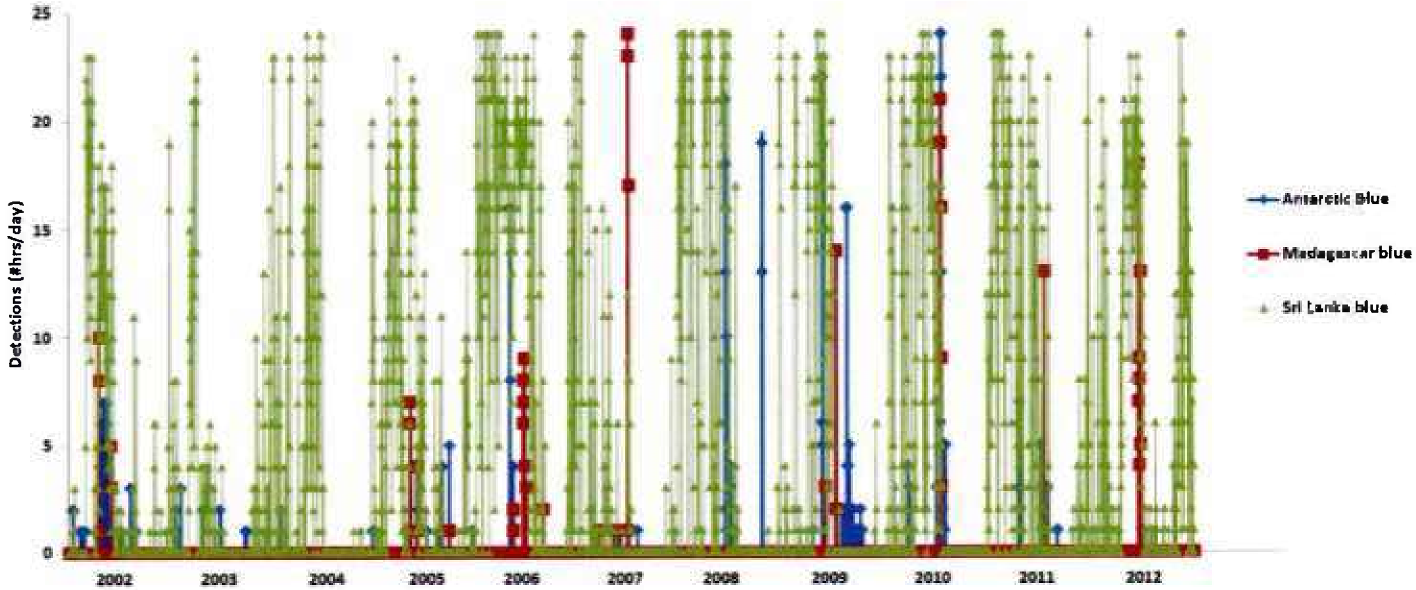
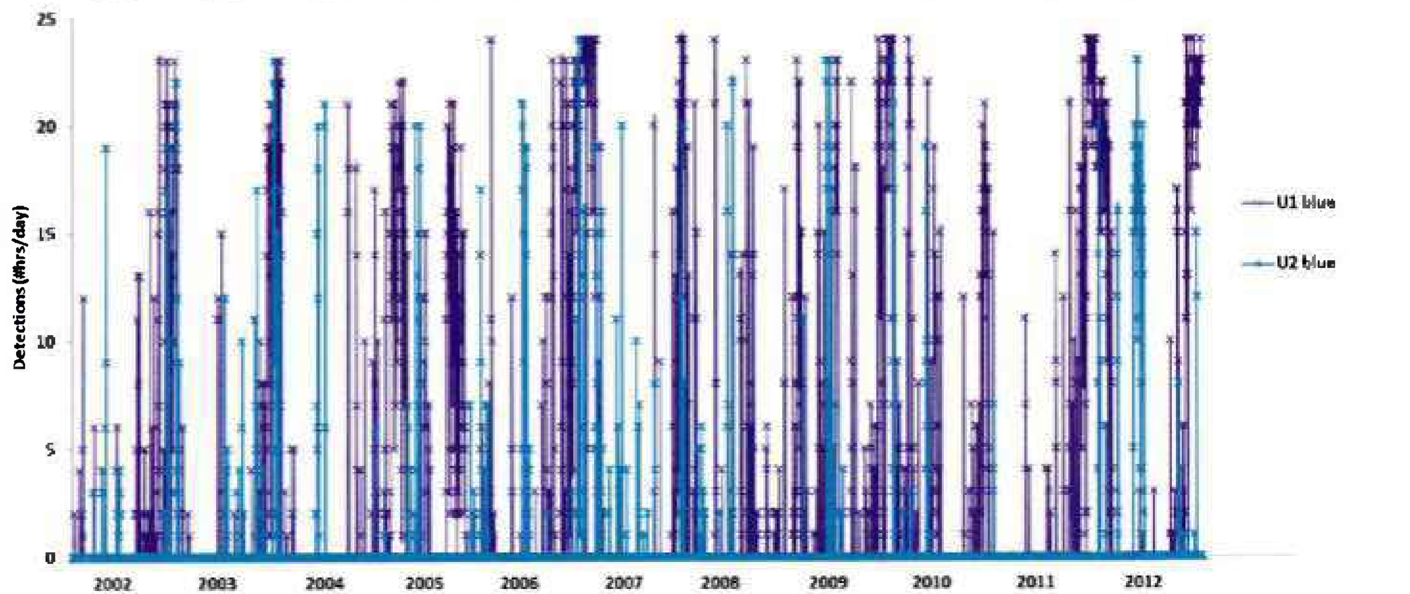


Figure 10. Long term spectral averages for A) a decade time series in the Indian Ocean over the full CTBTO IMS bandwidth (1-125 Hz), B) a decade time series in the Indian Ocean over a restricted bandwidth (80-125 Hz) to visualize the frequency decrease in blue whale vocalizations, and C) a six year time series in the Pacific Ocean over the full CTBTO IMS bandwidth. Images were created with a one hour window and 0.25 Hz resolution.

A)


Detections (#hrs/day)
Antarctic Blue
Madagascar blue
Sri Lanka blue
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

B)


Detections (#hrs/day)
U1 blue
U2 blue
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

C)

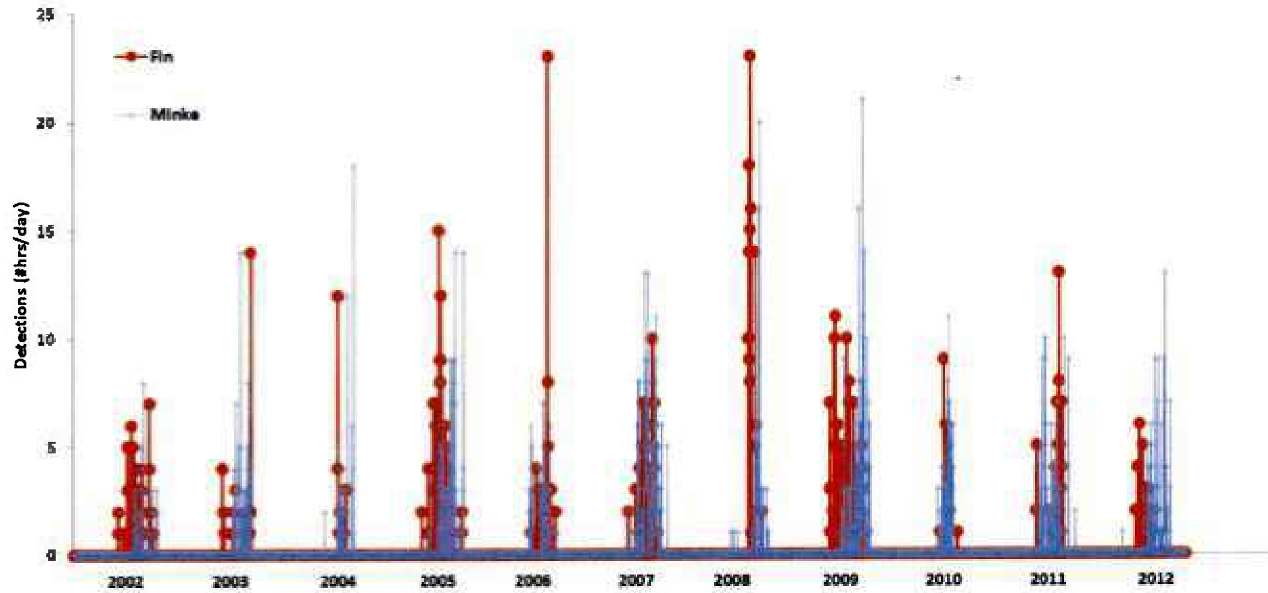


Figure 11. Hourly detection time series of marine mammal vocalization detected from H08N1 in the Indian Ocean at Diego Garcia. A) show data from blue whales, B) reflects detections from blue whales using the U1 and U2 calls, and C) displays data from fin and minke whales over a decade.

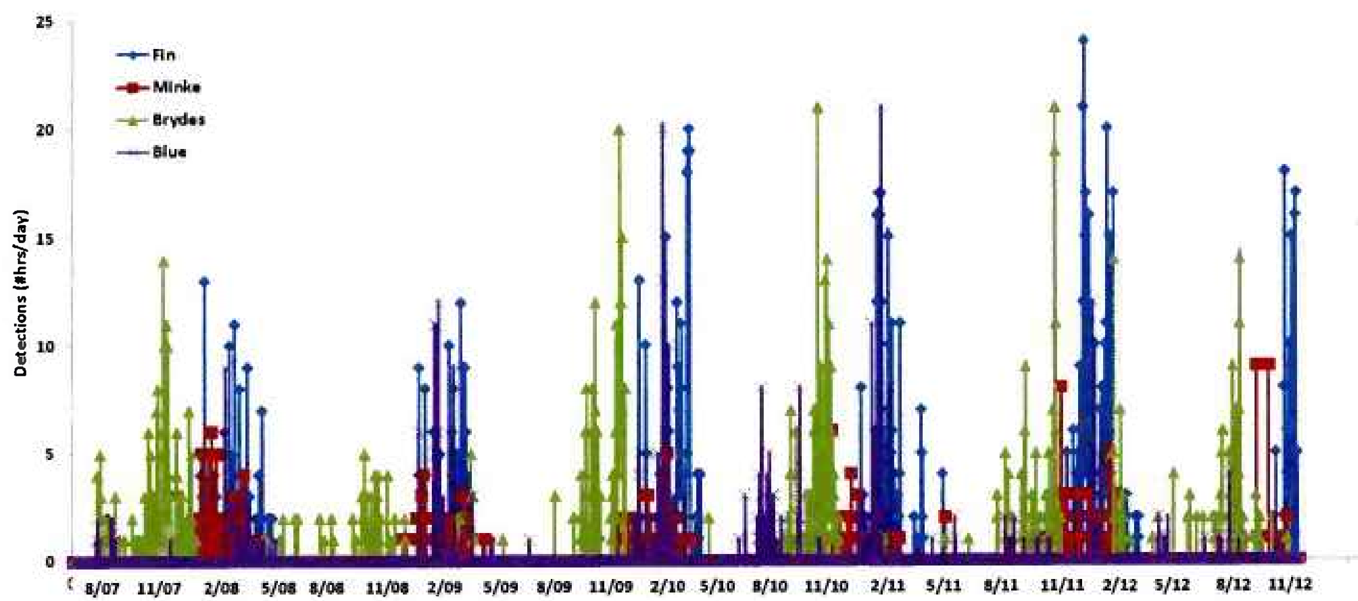


Figure 12. Hourly detection time series of marine mammal vocalization detected from H11N1 in the Pacific Ocean at Wake Island.